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Article

Advancing the Global Integration of Solar and Wind Power: Current Status and Challenges

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Abstract: The accelerating deployment of solar photovoltaic (PV) and wind power has fundamentally reshaped the landscape of global electricity systems. This article investigates the current status and emerging challenges associated with the large-scale integration of variable renewable energy (VRE) across diverse power systems worldwide. A special focus is then given to the issue of solar and wind curtailment, exploring both technical and economic implications and emphasizing the need for context-specific strategies to optimize system performance. The article further addresses two key technical challenges: maintaining system stability amid the displacement of synchronous generators, and meeting growing flexibility needs across multiple timescales as VRE shares increase. Finally, the article offers a set of policy recommendations aimed at enabling efficient, resilient, and sustainable integration of solar and wind energy. These include investment in grid infrastructure, reform of market structures, deployment of flexibility resources, and alignment of climate and energy policies. Together, these insights provide a comprehensive foundation for guiding the next phase of global energy transitions.

Keywords: Variable Renewable Energy (VRE), System Integration, Curtailment, Grid Flexibility, Energy Policy.

1. Introduction

Unlocking the full potential of large-scale solar photovoltaic (PV) and wind energy deployment necessitates the implementation of proactive and well-coordinated integration strategies [1-3]. Between 2018 and 2023, the installed capacities of solar PV and wind energy more than doubled, accompanied by a near doubling of their contribution to global electricity generation. Recognizing their pivotal role in the decarbonization of the energy sector, governments worldwide are increasingly positioning these renewable technologies as foundational components of future energy systems [4-7]. This rapid expansion is projected to persist through 2030, underpinned by favorable policy frameworks and significant cost reductions in both solar PV and wind technologies [8-11].

Maximizing the value derived from the accelerated deployment of solar photovoltaic (PV) and wind energy necessitates their effective integration into existing power systems [11-15]. Although electricity networks have traditionally been designed to accommodate fluctuations in demand, the integration of variable renewable energy (VRE) sources, such as solar PV and wind, introduces inherent supply-side variability driven by meteorological conditions [16-19]. Addressing this challenge will require a substantial enhancement of system flexibility through a coordinated portfolio of measures, including the utilization of dispatchable generation resources, strategic grid modernization, expansion of energy storage capacity, and the implementation of responsive demand-side management strategies [20-22].

Postponing the implementation of critical measures to facilitate the integration of solar photovoltaic (PV) and wind energy into power systems could jeopardize up to 15% of their projected generation by 2030 [20-24]. Such delays are also likely to result in a reduction of up to 20% in the anticipated decline of carbon dioxide (CO_2) emissions within the power sector [23-25]. Should integration efforts fall short of trajectories aligned with national climate commitments, as much as 2,000 terawatt-hours (TWh) of global variable renewable energy (VRE) output may be at risk by 2030, an amount equivalent to the combined solar and wind generation of China and the United States in 2023 [26-28]. This prospective loss primarily arises from increased technical and economic curtailment, along with delays in project grid connection. As a result, the share of solar PV and wind in the global electricity mix could stagnate at approximately 30% by 2030, in contrast to the 35% share achievable with timely integration efforts [29-31]. Should this shortfall be offset through heightened reliance on fossil fuel generation, it could significantly undermine decarbonization goals by diminishing CO_2 emissions reductions by up to 20% in the electricity sector [30-36].

Several studies have investigated the current status and challenges associated with advancing the global integration of solar and wind power. Table 1 provides a consolidated overview of key findings from recent research, highlighting critical insights into system integration strategies, operational challenges, and enabling policy frameworks.

Table 1. Summary of recent studies on the global integration of solar and wind power.

Ref.	Publisher	Highlighted	Target
[37]	Elsevier	▪ Development of a Hybrid VMD-LSTM Forecasting Model The study introduces a novel hybrid forecasting approach that combines Variational Mode Decomposition (VMD) with Long Short-Term Memory (LSTM) neural networks. This integration enhances input signal stationarity and noise resilience, addressing key challenges in multi-step-ahead renewable energy forecasting. ▪ Demonstrated Performance Improvements for Diverse Energy Sources Through application to real-world hourly power output data from hydro, wind, and solar stations in Hunan Province, China, the proposed VMD-LSTM model significantly outperforms conventional LSTM models. It achieves notable gains in prediction accuracy, as measured by improvements in the Nash-Sutcliffe Efficiency (NSE) and reductions in Root Mean Squared Error (RMSE) across all energy types.	Solar and wind
[38]	Elsevier	▪ Empirical Quantification of Integration Benefits Across Timescales Using a comprehensive, multi-decade dataset of hourly, daily, and monthly wind and solar productivity across Europe, the study demonstrates that optimal cross-country coordination can increase renewable capacity factors by 22% and reduce hourly output variability by 26%, underscoring the operational benefits of spatial integration at scale. ▪ Policy-Relevant Insights for Continental-Scale Energy Coordination The findings highlight the strategic advantage of treating renewable energy projects as components of an interconnected European system rather than as isolated national assets. This perspective offers actionable guidance for policymakers, emphasizing that coordinated planning across borders can reduce integration costs, improve efficiency, and accelerate the energy transition in response to climate and geopolitical pressures.	Solar and wind
[39]	Elsevier	▪ Evaluation of Battery Storage and Vehicle-to-Grid (V2G) as Grid-Enhancing Technologies The study investigates how integrating battery energy storage systems and V2G operations with intermittent renewable sources such as solar and wind can enhance grid stability and operational flexibility, particularly during peak demand periods. ▪ Strategic Insight into Future Renewable Integration By emphasizing the increasing importance of storage and V2G systems in global renewable energy expansion, the study provides strategic insights into how these technologies can support a reliable, renewable-dominated power grid, ensuring resilience and sustained performance amid high shares of intermittent resources.	Solar and wind

[21]	Springer	▪ Development of an Optimized Control Strategy for Grid-Connected Hybrid Wind-Solar Systems (HWSES) The study presents an optimized modeling and control framework for a grid-connected HWSES integrating a solar PV system with a wind-driven Doubly Fed Induction Generator (DFIG). By employing stator flux-oriented control of both the Grid Side Converter (GSC) and Rotor Side Converter (RSC), the proposed system ensures precise regulation and efficient grid integration. ▪ Simulation and Validation of a 2 MW HWSES in MATLAB/Simulink A 2 MW simulation model is developed and tested in the MATLAB/Simulink environment to validate the proposed strategies. The results demonstrate that the control schemes rapidly and accurately track maximum power, improve transient response, and enhance overall system stability, confirming the effectiveness of the hybrid system for reliable grid support.	Solar and wind
[40]	Wiley	▪ Proposal of a Dual-Energy Generation System for Integrated Grids The study introduces a hybrid renewable energy system, integrating solar photovoltaic (PV) and wind energy for grid-connected applications, specifically tailored to reduce energy wastage and meet increasing electricity demand. The approach is applied using real-world load data collected from multiple regions in Rajasthan, India. ▪ Demonstrated Cost Savings and Improved System Viability Simulation results show that the proposed hybrid system can achieve a 20% cost reduction compared to diesel and off-grid systems under a 10% annual capacity shortage allowance. The system's total cost of USD 49,500 is significantly lower than the alternative configurations evaluated, confirming its feasibility and cost-effectiveness for clean energy deployment in regional contexts.	Solar and wind

This article makes a significant contribution to the global discourse on the integration of solar and wind power by providing a comprehensive analysis of current advancements, technical barriers, and strategic policy directions. As renewable energy deployment accelerates worldwide, understanding how to effectively incorporate variable renewable energy (VRE) into diverse power systems has become a critical challenge. By drawing on empirical case studies and examining the evolving dynamics of grid operation, this article offers practical insights into overcoming the operational, economic, and regulatory complexities associated with high-VRE integration. The article’s contributions span from technical innovation and system-level analysis to forward-looking policy recommendations, forming a robust foundation to guide the next phase of global clean energy transitions.

A. Empirical Evidence of High-VRE Integration Success

The article presents real-world case studies from regions such as Denmark, Texas, and Chile, demonstrating that high levels of variable renewable energy (VRE) integration are not only feasible but already operational, challenging previous assumptions about technical limitations.

B. In-Depth Analysis of Curtailment Issues

It offers a focused examination of solar and wind energy curtailment, analyzing both technical and economic dimensions. The article emphasizes the importance of context-specific strategies to minimize curtailment and maximize system efficiency.

C. Identification of Core Technical Integration Challenges

The article explores two major technical obstacles: the need to maintain grid stability as synchronous generators are phased out, and the increasing demand for system flexibility across short to long timescales due to the variability of solar and wind generation.

D. Policy Framework for Scalable and Resilient VRE Integration

A comprehensive set of policy recommendations is provided, addressing the need for infrastructure investment, market reform, flexibility enhancement, and policy alignment, laying out a roadmap for supporting global energy transitions.

Thus, this article provides a multidimensional contribution to advancing the global integration of solar and wind power. It not only highlights the practical feasibility of high VRE shares through real-world examples but also offers a critical examination of the technical and operational challenges, such as curtailment, system stability, and flexibility requirements, that must be addressed to ensure reliable grid performance. Moreover, the article proposes a comprehensive policy framework to support scalable and resilient integration, emphasizing infrastructure development, market reform, and regulatory alignment.

2. Integration of High Shares of VRE Across Diverse Power Systems

Over a decade ago, many power systems across the globe were only beginning to deploy variable renewable energy (VRE) and were encountering integration challenges that were, at the time, largely uncharted. Today, however, a growing number of power systems have successfully navigated these obstacles, with several achieving levels of VRE penetration once deemed unattainable. Attaining high shares of solar and wind energy in the electricity mix is no longer a theoretical scenario, it has become a demonstrated reality in numerous jurisdictions [41,42]. In 2023, regions such as Denmark, Texas, South Australia, Ireland, Spain, and Chile reported annual electricity generation from solar and wind exceeding 30% [41-44]. Furthermore, these and other systems are increasingly reaching record levels of hourly VRE penetration, during which solar and wind collectively supply the majority, or, at times, nearly the entirety of electricity demand for sustained periods throughout the year.

The ongoing expansion of variable renewable energy (VRE) integration is occurring across power systems with diverse renewable resource endowments. For instance, countries such as Denmark, Ireland, Great Britain, and Morocco have predominantly scaled up VRE generation through wind power. Similarly, wind energy remains the slightly dominant contributor in the People's Republic of China (hereafter 'China') and Spain. Conversely, jurisdictions such as Chile, California, Viet Nam, and, to a lesser extent, Australia, have prioritized solar photovoltaic (PV) as their principal VRE source [44-47].

A. Grid Development Imperatives

The expansion, modernization, and strategic upgrading of electricity grids are essential prerequisites for enabling solar and wind energy to effectively meet growing global electricity demand. To accommodate the rising deployment of variable renewable energy (VRE), grids must be extended and reinforced to facilitate the connection of newly commissioned solar and wind power plants, ensure the reliable transmission of electricity to end-users, and maintain real-time balance between supply and demand. Grid infrastructure also plays a pivotal role in enhancing system flexibility by enabling the geographical smoothing of VRE generation profiles and mitigating local intermittency through spatial diversity [47-50].

However, delayed investment in grid infrastructure is already manifesting significant operational and economic repercussions across power systems worldwide. Despite nearly doubling global investment in renewables between 2010 and 2023, grid-related investment stagnated at approximately USD 300 billion annually from 2015 until 2024, when it rose to USD 400 billion. This chronic underinvestment has created substantial bottlenecks, with over 1,500 GW of advanced-stage solar and wind projects awaiting grid connection as of mid-2023 [51-53].

Moreover, grid congestion has emerged as a costly and persistent challenge. Addressing real-time congestion often necessitates the dispatch of suboptimal power plants, leading to substantial short-term costs and necessitating major long-term capital investments. In the United States, for example, congestion management costs surged from USD 6 billion in 2019 to nearly USD 21 billion in 2022, equating to over USD 4 per megawatt-hour (MWh) of electricity consumed. Comparable economic burdens have been observed in Germany and Great Britain, where annual congestion costs have exceeded multi-billion-dollar thresholds, amounting to roughly USD 8 per MWh [54,55]. In addition, deferred grid development elevates the risk of power outages, which collectively impose an annual economic cost of at least USD 100 billion globally, equivalent to approximately 0.1% of global GDP.

These figures underscore the urgent need for targeted, forward-looking grid investment strategies to ensure the reliable, affordable, and sustainable integration of VRE at scale [55,58].

B. Rising Demand for Power System Flexibility

Power system flexibility has become a critical enabler for managing the increasing variability and uncertainty introduced by high shares of variable renewable energy (VRE). Flexibility is broadly defined as the capacity of a power system to maintain a reliable and cost-effective balance between electricity supply and demand across all relevant temporal scales. This balancing act involves dynamically adjusting both generation and demand in response to fluctuations, ranging from short-term variations to longer-term resource constraints [59-62].

Flexibility requirements span multiple timescales for instance, managing intraday supply-demand imbalances, such as hourly solar generation peaks and troughs, to navigating prolonged periods of resource scarcity, such as droughts affecting hydropower availability. Under the Announced Pledges Scenario (APS), which reflects countries' stated climate and energy goals, global flexibility needs are projected to grow significantly by 2030, with even steeper increases anticipated in subsequent decades [63-65]. At the shorter end of the timescale spectrum, near-term flexibility requirements, specifically those arising from intraday fluctuations are expected to nearly double by 2030 relative to current levels. The increasing deployment of solar PV is a major driver of this shift, due to its inherently variable and diurnal generation profile [64-67]. These short-term flexibility needs are anticipated to be largely addressed through existing solutions, including battery energy storage systems, demand response programs, and, to a lesser extent, strategic curtailment of renewable output.

Conversely, growth in long-term, seasonal flexibility requirements is projected to be more moderate by 2030 [65-68]. However, in countries with elevated VRE penetration and substantial electricity demand for end-uses such as heating and cooling, seasonal variability may emerge as a significant system planning challenge. This is already evident in jurisdictions such as the United States, where the North American Electric Reliability Corporation (NERC), in its 2024 Summer Reliability Assessment, designated multiple regions as facing "Elevated Risk," partly due to projected increases in electricity demand linked to extreme temperature events [68-70].

3.Special Focus: Curtailment of Solar PV and Wind Energy

Curtailment of variable renewable energy (VRE), particularly from solar photovoltaic (PV) and wind sources, has garnered increasing attention in recent years due to its potential economic implications, most notably, the reduction in revenue streams for both existing and prospective renewable energy projects. Effectively managing curtailment requires a nuanced understanding of the specific power system conditions and the degree of VRE penetration, as these factors significantly influence both the occurrence and impact of curtailment events [71-73]. In the context of power system operations, curtailment can generally be classified into two categories. Technical curtailment is initiated by system operators to preserve grid reliability and ensure secure electricity supply, typically in response to constraints such as transmission congestion, voltage instability, or localized oversupply. Economic curtailment, on the other hand, occurs when generators voluntarily reduce output in response to unfavorable market signals, such as negative or low electricity prices [74-76]. In both cases, curtailment functions as one of several mechanisms employed to balance real-time supply and demand and to maintain system security.

While curtailment can be a necessary operational tool, high levels of curtailed generation may result in considerable volumes of clean energy being left unused, thereby diminishing revenues for renewable energy producers. Moreover, curtailment may inadvertently increase CO_2 emissions when fossil-fuel-based generators are redispatches to resolve system constraints that might otherwise be addressed with greater system flexibility [77-79]. These outcomes pose potential setbacks for countries aiming to meet decarbonization targets, as diminished financial viability for VRE projects could decelerate deployment, and limited displacement of fossil-based generation undermines emissions reductions.

To prevent the erosion of investor confidence and ensure continued deployment of variable renewable energy (VRE) assets, it is imperative to implement operational measures that mitigate unnecessary curtailment while maintaining grid reliability. One notable example is the Automatic Power Reduction System (SRAP) introduced in 2022 by Spain's transmission system operator, Red Eléctrica [80-82]. This innovative, voluntary mechanism addresses real-time grid congestion by enabling dynamic curtailment of participating VRE plants only when system contingencies actually materialize.

By September 2024, the SRAP had successfully prevented the curtailment of over 3.4 terawatt-hours (TWh) of renewable energy that would have otherwise been curtailed under a purely preventive redispatch regime [81-83]. This operational refinement has contributed to keeping monthly technical curtailment of renewable energy below 2% in Spain's peninsular system, even as the share of VRE generation approached 40% in 2023. The Spanish example illustrates how real-time, adaptive grid management strategies can simultaneously reduce system costs, preserve clean energy output, and support the economic viability of renewable investments [84,85].

However, in systems with high or very high VRE shares, curtailment is increasingly recognized as a rational and sometimes economically optimal outcome. For example, in contexts where structural oversupply occurs such as during midday solar PV surpluses, minimizing curtailment to near-zero levels may conflict with broader system cost optimization and flexibility strategies. Therefore, in such systems, curtailment should not be viewed solely as a failure or inefficiency, but rather evaluated in relation to key contextual variables including VRE penetration levels, transmission capacity, demand profiles, and the availability of flexible resources.

4.Challenges: System Stability and Expanding Flexibility Requirements

As power systems advance toward higher phases of variable renewable energy (VRE) integration, two critical and increasingly prominent challenges are emerging from the standpoint of system performance and resilience: the need to maintain system stability and to address escalating flexibility requirements across multiple temporal scales. Historically, both attributes were inherently provided by large-scale hydroelectric and fossil-fuel-based thermal generators. However, as unabated fossil-fuel-fired assets are progressively decommissioned to meet decarbonization goals, alternative mechanisms must be employed to fulfill these essential system functions.

System stability refers to the grid's capacity to restore equilibrium following a disturbance, ensuring frequency and voltage remain within operational tolerances after events such as generator outages or line faults. Traditionally, the large synchronous inertia provided by rotating masses in conventional thermal and hydro generators has played a key role in buffering such disturbances. With the increasing displacement of these assets by non-synchronous VRE sources, stability services must now be procured from a broader portfolio of technologies, including advanced battery energy storage systems, grid-forming inverters, synchronous condensers, and even VRE facilities equipped to provide ancillary services. Concurrently, operational protocols and real-time system management practices must evolve to support stability under these new conditions.

On the other hand, flexibility, the system's ability to respond to changes in net load across different timescales, is becoming increasingly complex. In the earlier phases of VRE integration, flexibility demands were primarily concentrated in the minutes-to-hours timeframe, where ramping capabilities of dispatchable resources were sufficient. However, as systems enter Phase Four and beyond, flexibility needs in this range intensify, and new challenges emerge in longer timescales spanning days, weeks, or even seasons. These longer-duration flexibility requirements are critical for managing extended periods of low VRE availability (e.g., low wind or solar output) or sustained oversupply during times of high renewable generation and low demand.

A. Impacts of Displacing Synchronous Generators on System Stability

The displacement of large synchronous generators by converter-connected renewable energy technologies poses fundamental challenges to power system stability. The stable operation of large-scale power systems depends on a set of core attributes collectively referred to as system strength, comprising three critical components: physical inertia, a stiff voltage waveform, and the ability to sustain high fault current levels. Traditionally, these functions have been inherently provided by synchronous generators most notably those in large hydroelectric and thermal power plants. As the share of variable renewable energy (VRE) continues to grow, these essential system attributes must increasingly be sourced from alternative assets.

Unlike synchronous generators, VRE facilities as well as battery storage systems and high-voltage direct current (HVDC) interconnectors, interface with the grid via power electronic converters as illustrated in Figure 1. While these converter-connected resources are highly versatile and capable of delivering a broad range of system services, including voltage and frequency regulation, fast fault response, and enhanced controllability, they do not inherently contribute to system strength. Consequently, as traditional synchronous units are progressively displaced by inverter-based resources, power systems may face growing vulnerabilities across all dimensions of system strength.

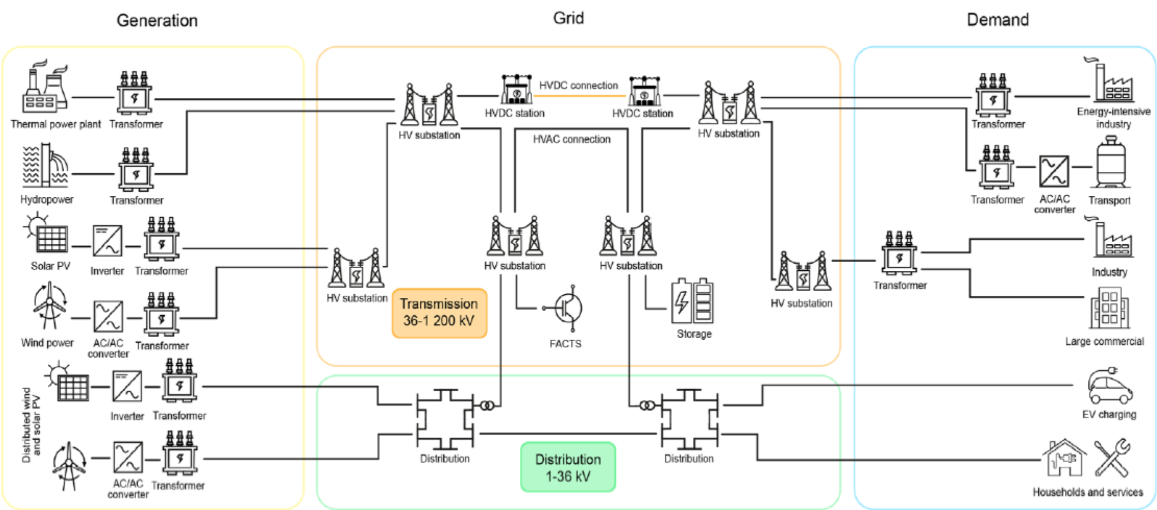

Figure 1. Essential elements of electrical networks [86].

The central grid section is divided into high-voltage transmission and medium- to low-voltage distribution. High-voltage substations and HVAC/HVDC connections are critical for long-distance electricity transport, with HVDC lines particularly effective for integrating large-scale renewables across regions. Flexible AC Transmission Systems (FACTS) are shown as essential components that enhance voltage regulation and power flow control, capabilities increasingly important as VRE shares grow. Energy storage systems are also depicted within the grid, indicating their dual function in improving system flexibility and providing services such as frequency response, load balancing, and peak shaving. The distribution system (1–36 kV) connects end-users and accommodates growing levels of decentralized energy resources like rooftop solar and electric vehicle (EV) charging stations, adding complexity to grid management.

A primary concern is the decline in system inertia, which directly affects the system's ability to resist rapid changes in frequency following a disturbance. Inertia is derived from the kinetic energy stored in the rotating masses of synchronous generators and is a critical factor in determining the rate of change of frequency (RoCoF) during events such as generator or line outages. In systems with high inertia, frequency changes more gradually, allowing time for protective and corrective responses. However, in systems with low inertia due to a reduced presence of synchronous machines, frequency can deviate more abruptly, increasing the risk of equipment malfunction or large-scale blackouts.

B. The expansion of variable renewable energy (VRE) positively impacts flexibility.

The growth of variable renewable energy (VRE), particularly solar photovoltaic (PV) and wind, has significantly intensified the need for flexibility across all operational timescales within power systems. Traditionally, variability in electricity systems was predominantly driven by demand fluctuations, but this paradigm is shifting. The ongoing electrification of major end uses, such as heating, cooling, and transportation, is contributing to more pronounced and less predictable swings in electricity demand. Climate change further exacerbates this variability, particularly by amplifying evening peak loads and seasonal energy consumption for space conditioning, especially in hotter climates like Southeast Asia and India.

As the share of VRE in the generation mix increases, supply-side uncertainty and mismatch between generation and demand become more frequent and persistent. This is especially evident during extended periods of low renewable output, such as the so-called "dark doldrums" (or Dunkelflaute), already observed during winter in regions like Europe and Japan, where both solar and wind availability drop simultaneously. These conditions underscore the growing importance of long-duration flexibility, extending beyond traditional intra-day balancing to include multi-day, weekly, and seasonal timescales. In contrast, systems with lower VRE penetration typically experience less pronounced flexibility needs over these extended horizons. Figure 2 provides a comparative overview of how flexibility needs and their underlying drivers are evolving across selected regions under the APS from 2022 to 2030.

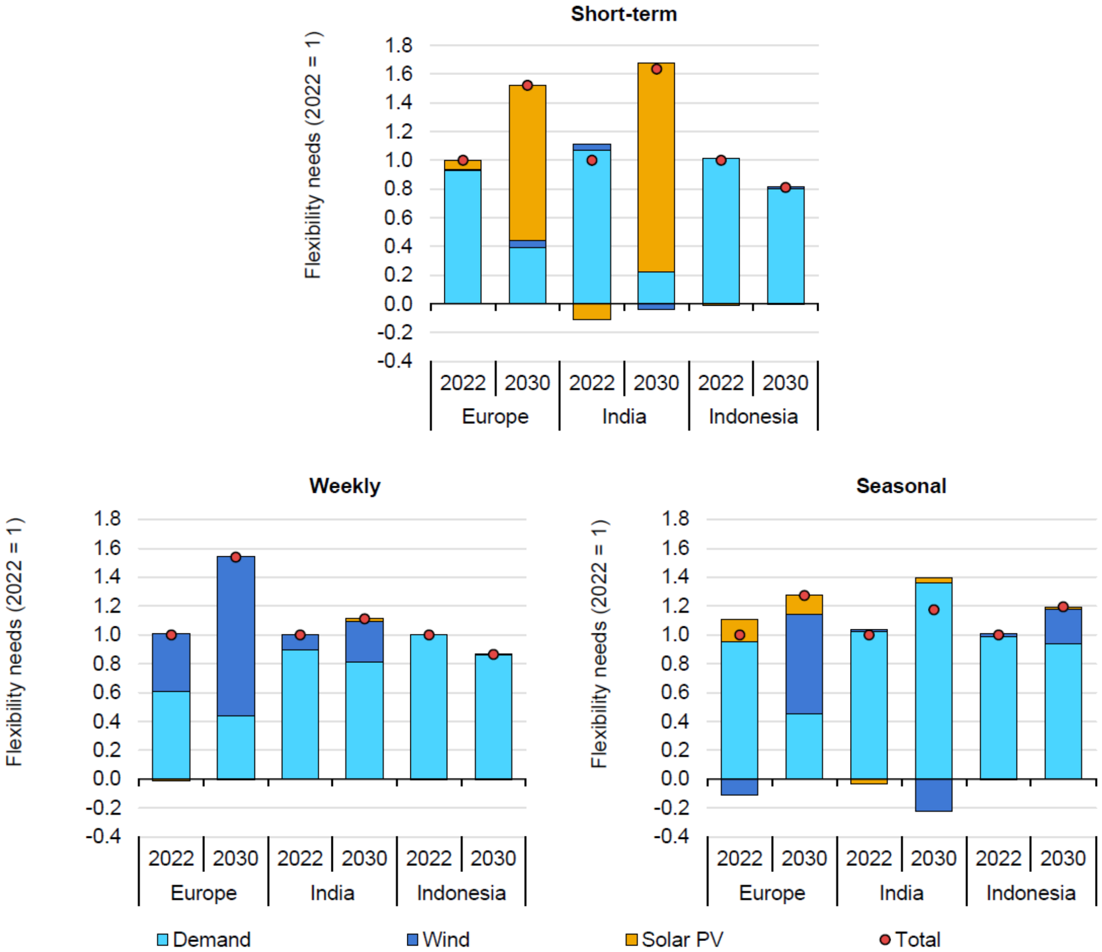

Figure 2. A comparative overview of how flexibility needs and their underlying drivers across selected regions under the APS from 2022 to 2030 [86].

Regional diversity in resource endowments and demand structures gives rise to distinct variability patterns, but across nearly all contexts, flexibility requirements are expected to outpace demand growth, particularly under the Announced Pledges Scenario (APS). In this scenario, short-term flexibility needs, defined as fluctuations occurring within the course of a day are projected to increase by at least 50% in Europe and India by 2030, with solar PV identified as the primary driver. Weekly flexibility requirements are also expected to grow by over 50% in Europe, largely attributable to the dominance of wind energy, which exhibits more stochastic generation patterns over multi-day periods. Furthermore, seasonal flexibility demands are projected to increase by at least 15% between 2022 and 2030 in regions such as Europe, India, and Indonesia. In the latter two, the principal contributor is the surge in electricity demand for cooling, as a growing proportion of the population gains access to air conditioning, underscoring the intertwined effects of development, electrification, and climate adaptation. These dynamics highlight the imperative to strategically plan for and invest in flexibility solutions, including storage technologies, demand-side management, grid reinforcement, and sector coupling, to ensure that power systems can reliably accommodate rising shares of VRE while meeting evolving consumption patterns.

As the global power sector undergoes a transformative shift toward high shares of solar and wind energy, ensuring system stability and meeting expanding flexibility requirements have emerged as central challenges. The displacement of conventional synchronous generators diminishes the natural provision of inertia, voltage control, and fault current, which historically underpinned grid resilience. Simultaneously, the variable and weather-dependent nature of solar PV and wind amplifies the complexity of balancing supply and demand across all timescales, from seconds to seasons.

Addressing these challenges demands a systemic and forward-looking approach. Grid operators and policymakers must adopt a diversified portfolio of solutions, including advanced inverter technologies, fast-responding storage, grid-forming resources, demand-side flexibility, and enhanced interconnection capacity. Additionally, evolving operational practices, regulatory frameworks, and market designs will be essential to ensure that power systems can maintain reliability and cost-effectiveness while accelerating the decarbonization process.

5. Policy Recommendations

To ensure the successful global integration of solar and wind power, coordinated and forward-looking policy interventions are essential. The following recommendations outline key policy priorities for enabling high shares of variable renewable energy (VRE) while maintaining power system reliability, economic efficiency, and climate goals:

A. Accelerate Investment in Grid Infrastructure

Policymakers must prioritize large-scale investments in transmission and distribution infrastructure to accommodate the spatial distribution of solar and wind resources. This includes upgrading existing networks, deploying high-voltage direct current (HVDC) interconnectors, and expanding cross-border transmission corridors to enable resource sharing and geographic balancing.

B. Strengthen Power System Flexibility Across All Timescales

Governments should support the deployment of flexibility resources such as battery storage, pumped hydro, demand response, and flexible peaking capacity. Regulatory frameworks should incentivize investments that provide system services across multiple timescales, from intra-day ramping to seasonal balancing and reward fast-responding technologies.

C. Modernize Market Design and Ancillary Services

Electricity markets must evolve to recognize and compensate the full range of services needed in high-VRE systems. This includes the provision of inertia, voltage support, fast frequency response, and ramping capabilities. Market reforms should enable participation of inverter-based resources, storage systems, and distributed energy assets in ancillary service markets.

D. Promote Sector Coupling and Electrification Synergies

Policymakers should develop integrated energy strategies that link electricity with heating, cooling, transport, and industry (sector coupling). Electrification of end uses, when aligned with VRE generation profiles (e.g., daytime EV charging or flexible heat pumps), can enhance system integration and reduce curtailment.

E. Support Innovation in Grid-Forming and Smart Inverter Technologies

Public and private R&D investment should be directed toward advanced inverter technologies capable of grid-forming functions. These innovations can enhance stability in low-inertia systems and reduce the need for synchronous generation, enabling greater displacement of fossil fuels.

F. Establish Long-Term Planning and Regional Coordination

Governments must adopt long-term, integrated energy planning processes that include VRE resource mapping, transmission development, and reliability assessments. Regional cooperation, especially in interconnected systems can facilitate more efficient integration and reduce costs through shared balancing resources and markets.

G. Design Curtailment-Tolerant Business Models

Acknowledging that some level of curtailment is economically efficient at high VRE shares, policies should ensure that power purchase agreements (PPAs), tariff structures, and support mechanisms reflect this reality and maintain investment signals for renewable developers.

H. Enhance Data Transparency and System Visibility

Grid operators and policymakers should ensure transparent access to real-time and historical data on system operations, curtailment, and flexibility needs. Enhanced visibility supports informed investment, regulatory oversight, and public trust.

I. Implement Workforce and Institutional Capacity Building

Investing in human capital is critical. Training programs for system operators, regulators, engineers, and technicians must be updated to reflect the complexities of high-VRE systems, including digital technologies, forecasting tools, and cyber-physical grid management.

J. Align Climate and Energy Policies to De-Risk Investment

Governments should ensure that climate targets, renewable energy goals, and regulatory frameworks are mutually reinforcing. Clear policy signals, streamlined permitting processes, and stable financial incentives are crucial to mobilize private capital and de-risk large-scale VRE integration.

The effective global integration of solar and wind power is not solely a technological challenge but a policy imperative. As variable renewable energy (VRE) continues to scale rapidly, forward-thinking and coordinated policy measures are essential to unlock its full potential while safeguarding system reliability, economic efficiency, and climate objectives. The recommendations outlined, ranging from grid infrastructure investment and market reform to flexibility enhancement and sector coupling, form a comprehensive policy framework that enables the transition to high-VRE power systems. Implementing these policies will not only facilitate the smooth integration of solar and wind energy but also create a more flexible, resilient, and low-carbon electricity sector. Strategic planning, regulatory innovation, and sustained investment, coupled with regional cooperation and institutional capacity building will be critical to overcoming the technical, economic, and operational challenges ahead. With decisive action, policymakers can ensure that the integration of solar and wind power becomes a cornerstone of a secure, affordable, and sustainable global energy future.

5.Conclusion

The global integration of solar and wind power has reached a pivotal stage. As more countries move beyond initial deployment phases, the emphasis must now shift from expansion to systemic optimization and resilience. This article has shown that high shares of variable renewable energy (VRE) are not only achievable but already in operation across several advanced power systems. Case studies from Denmark, Texas, South Australia, and Chile underscore that with appropriate infrastructure and governance frameworks, VRE penetration levels exceeding 30% are manageable and beneficial. These successes offer critical lessons, particularly for emerging economies seeking to leapfrog into cleaner, more sustainable energy futures.

However, the transition is not without its technical and economic hurdles. One of the most pressing issues is the curtailment of solar and wind energy, a phenomenon that can undermine the financial viability of renewable investments and delay decarbonization goals. While curtailment is sometimes necessary for grid security, persistent or unmanaged curtailment reflects deeper structural limitations, such as inflexible market designs, insufficient grid capacity, or inadequate forecasting and scheduling practices. A more mature approach to curtailment, recognizing when it is economically efficient and when it signals a need for reform, is essential for maximizing the value of renewable resources.

Simultaneously, the shift away from synchronous generation presents complex stability and flexibility challenges. As rotating inertia diminishes and non-synchronous inverter-based generation grows, power systems must adopt new mechanisms to maintain frequency, voltage, and fault resilience. The traditional operational paradigm must evolve to embrace solutions such as grid-forming inverters, fast frequency response, synchronous condensers, and coordinated demand-side management. Moreover, flexibility requirements are expanding across all timeframes, from seconds to seasons, demanding a broader portfolio of responsive resources including storage, flexible generation, electrified end-uses, and dynamic network management.

Addressing these multifaceted challenges requires more than technology, it demands visionary policy leadership. The policy recommendations outlined in this article call for transformative action across infrastructure investment, market reform, sector coupling, and institutional capacity building. In particular, aligning energy, climate, and economic development policies can create a stable and predictable environment for renewable investment, while also ensuring that system integration keeps pace with capacity growth. In conclusion, the global energy transition is accelerating, but its success hinges on proactive and adaptive approaches to VRE integration. Solar and wind power offer not only a path to decarbonization but also an opportunity to build more flexible, reliable, and inclusive energy systems. With the right mix of policies, technologies, and international collaboration, the vision of a clean, resilient, and affordable global energy future is within reach.

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